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In-Network Performance of Handheld Mobile Terminals

Jesper Ødum Nielsen and Gert Frølund Pedersen

***Abstract*—This paper considers a realistic evaluation of the power mobile handsets are able to transmit and receive. It has been suggested to use the so-called total radiated power (TRP) and the total isotropic sensitivity (TIS) for the uplink and downlink, respectively, which may be seen as special cases of the general mean-effective-gain (MEG) measure. These measures are computed from the spherical radiation pattern of the handset and the different measures are obtained by using different models of the mobile propagation environment. In this paper, the results obtained via the spherical radiation patterns are compared with the equivalent performance obtained in a live Global System for Mobile Communications (GSM) network using data from the Abis network interface. This method does not require altering of the handsets and the testing uses normal calls in the network. The investigation is based on measurements with four different commercially available handsets carried out in two different indoor environments and involving 22 test users. In addition, a series of measurements were also made with a phantom simulating the handset user, allowing a test of how well the phantom represents the average user.**

***Index Terms*—GSM handset performance, mean effective gain, phantom user, radiation patterns, total isotropic sensitivity, total radiated power.**

I. Introduction

It is well known that the performance of today's mobile handsets vary significantly in terms of the power they are able to transmit and receive [1]. This is important since the network coverage and interference level in the network is influenced by the ability of the handsets to receive and transmit, and furthermore, the battery lifetime of the individual handsets may be reduced unnecessarily if much power is wasted in antenna losses instead of being radiated.

Realistic performance evaluation of a handset is difficult because of the multipath propagation channel where the signals may be received from many directions and with different polarizations [2]. A performance measure that takes this into account is the so-called mean effective gain (MEG) that is defined as the mean power received by the handset to the mean power received by a reference antenna, where the mean values are computed for a realistic route in a mobile environment [3].

Evaluation of handsets in this way has some practical difficulties, which may limit its applicability, such as setup of measurement equipment, involvement of test users and, furthermore, a license may be required for the intended frequency spectrum.

Alternatively, the MEG may also be computed from the spherical radiation pattern of the handset and a model of the mobile environment [4]. One of the main advantages of this approach is that it separates measurements involving the handsets from measurements involving the mobile channel, provided that a suitable model of the channel exists.

Performance evaluation of handsets based on spherical radiation patterns has been adopted by a working group of European Cooperation in the Field of Scientific and Technical Research (COST) 259 and its successor COST 273 [1]. Similarly, the Cellular Telecommunications and Internet Association (CTIA) has been working on a certification of mobile handsets in terms of the so-called total radiated power (TRP) relevant for the uplink (UL) and the total isotropic sensitivity (TIS) for the downlink (DL) (see [5]). These latter measures may be seen as special cases of the MEG computed from the radiation pattern. Unlike the general MEG, the TRP and TIS does not take into account the directional and polarization properties of the handset antenna and the mobile environment.

When the performance of a handset is evaluated the user of the handset is important. It has been demonstrated previously that the performance is highly dependent on the user, where differences from user to user of up to 10 dB have been found [6]–[9]. The so-called body loss (BL) describes the difference (in decibel) in received power when the user is present and when no user is present. The BL varies not only from user to user but the mean BL also varies from handset to handset, depending on the design [10]–[12].

The current paper presents the results of an investigation concerning the performance of four commercially available handsets. The performance evaluation is based on measurements in a live Global System for Mobile Communications (GSM) network, utilizing the measurement capabilities of the network. In this way, the handsets are evaluated in a realistic way since the measurements take place during normal calls. Furthermore, modifications to the handsets are unnecessary and adding cables to the handsets is avoided, which would typically be necessary for channel sounder-based measurements. Adding conducting cables to a small handset is problematic since this will change the radiation pattern significantly [13].

The measurements involved 22 test users, where for each user measurements were made in two different mobile environments using the four handsets and both sides of the user's head. A series of measurements was also carried out with the handsets in free space and one where the handsets were next to a phantom simulating the head and hand of the user. The

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obtained BL values are analyzed with respect to the antenna type, link direction, side of the user's head, position of the user's hand, and variation among users. Furthermore, it is investigated to which degree the phantom represents the average user.

In addition, the spherical radiation patterns of the tested handsets were measured in an anechoic room, both in free space and including the phantom. This allows a comparison between the performance of the handsets in the real network and the results of the proposed evaluation methods based on spherical radiation patterns, i.e., the TIS, the TRP, and the MEG for different channel models.

II. MEG From Radiation Patterns

The MEG was introduced as a method for evaluating the performance of antennas in a mobile environment, and is defined as the ratio of the average power received by the antenna under test to the average power received by some reference antenna, while they are both moving in the same environment [3]. This method of evaluating antennas directly via measurements in the mobile environment is employed in the in-network measurements, described in Section IV.

It is also possible to compute the MEG using spherical radiation patterns of the antennas, in which case, the reference antennas are two hypothetical isotropic antennas matched to the θ and ϕ polarizations, respectively [2], [4]. The MEG is then expressed as

$$\Gamma = \frac{\oint_{\mathrm{S}} G_\theta(\Omega) Q_\theta(\Omega) + G_\phi(\Omega) Q_\phi(\Omega) d\Omega}{\oint_{\mathrm{S}} Q_\theta(\Omega) + Q_\phi(\Omega) d\Omega}. \quad (1)$$

Using ψ to denote either θ or ϕ, $G_\psi(\Omega)$ is the power gain in the ψ polarization, defined as the measured power in the direction Ω normalized to the total input power. The interpretation of $Q_\psi(\Omega)$ depends on the link direction. For the DL, $Q_\psi(\Omega)$ is the average power incident on the handset from the direction Ω in the ψ polarization. For the UL, $Q_\psi(\Omega)$ is the power received on average by the base station stemming from the mobile transmitting in the direction Ω and in the ψ polarization.

The cross polarization difference (XPD) is defined as the ratio of power in the θ polarization to the power in the ϕ polarization. Since the MEG is a ratio of power values, only the XPD and the distribution of power versus direction are important in the model of the power density $Q_\psi(\Omega)$. In this paper, five models have been used.

- HUT: A model based on numerous outdoor to indoor measurements in the city of Helsinki, Finland [14]. In this model, the variation versus azimuth angle is assumed uniform and nonuniform versus elevation angle. It has an XPD of 10.7 dB.
- AAU: A model based on numerous outdoor to indoor measurements in the city of Aalborg, Denmark [15]. This model includes variation in both azimuth and elevation angle, and has an XPD of 5.5 dB.
- Iso: The isotropic model implies equal weighting of power versus direction in both polarizations and with an XPD of 0 dB. This model results in MEG values equivalent to the TRP and TIS, for the UL and DL, respectively.
- Rect0: The rectangular model has uniform weighting inside the window defined by $45^\circ \leq \theta \leq 135^\circ$ and $0^\circ \leq \phi < 360^\circ$, and zero weighting outside this window, where θ is the elevation angle measured from the vertical axis and ϕ is the azimuth angle. The XPD is 0 dB for this model [5].
- Rect6: Similar to Rect0, but with an XPD of 6 dB.

For mobiles operating in an indoor environment and communicating with a base station located outdoors, the power can in many cases be expected to be transmitted mainly through building openings such as windows and doors, and hence the power distribution will be nonuniform. Also, the radiation patterns of mobile handsets in use can be expected to be nonuniform due to the blocking of the user in normal handheld operation. Therefore, the received power can be expected to vary depending on the orientation of the handset/user in the environment.

Although the user orientation in the environment in general is arbitrary, the variation in power over different orientations may be significant. In order to evaluate the power variation models with nonuniform power distribution are needed.

A. Anechoic Room Measurements

The measurements of the spherical radiation patterns were performed in a large anechoic room using a GSM tester (Rohde & Schwarz CMU 200) and a positioning device with two axes. Both the GSM tester and the positioning device are controlled from software running on an SUN workstation, allowing automatic measurement of the complete spherical radiation pattern in both the θ and the ϕ polarization. The GSM tester, acting as a base station, measures the UL power while the DL measurements are obtained from the receiver power levels (RxLev) measured by the handset, as required by the GSM standard, see also Section III. In this way, the measurements can be made without attaching cables, etc., to the handsets that will change the radiation pattern [13]. Furthermore, the measured values are actually transmitted/received power levels including antenna-matching losses, the efficiency of the antenna, incorrect transmit power level (TPLs), etc.

The UL power measurements performed by the CMU have been calibrated using a precision power meter. The precision of the power measurements made by the handsets in the DL is discussed in Section III-C.

The handsets measured are commercially available and represent some of the main handset types used today. The handsets are labeled as follows:

- A: large handset with an external, normal mode helix antenna;
- B: large handset with an integrated antenna;
- C: small handset with an integrated antenna;
- D: small handset with an external, normal mode helix antenna;

where the "small" handsets are about 10 × 4.5 cm, and the "large" handsets are about 13 × 4.5 cm. All of the handsets are of the "candy bar" type. The integrated antennas are placed near

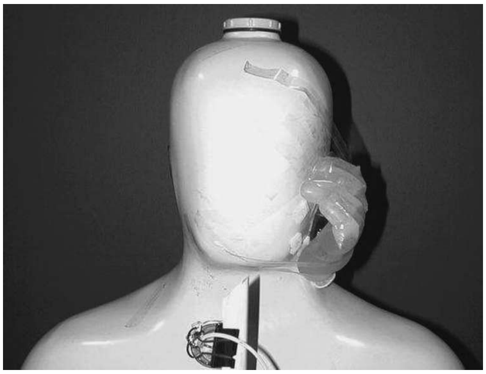


Fig. 1. Phantom and hand.

the top and at the back of the handset while the helix antennas are placed at the top of the handsets.

All the measurements were made on GSM-1800 channel 698, i.e., at about 1842 MHz for the DL and 1747 MHz for the UL. The spherical radiation pattern was sampled using increments of 10° in both the azimuth angle ϕ and the elevation angle θ. The handsets were measured both in free space and next to a phantom simulating the user of the handset. The phantom series of measurements were made with a commercially available phantom modeling the head, shoulders, and part of the human chest [16]. The phantom is hollow and filled with human tissue-simulating liquid, as specified for specific absorption ratio (SAR) testing [16]. In addition to the head and body phantom, a hand was also simulated by a rubber glove filled with the same liquid as the phantom. During measurements, the phantom hand was approximately 5 cm below the top of the handset, the same as the "low" position used during the network measurements (see Section III). The handset was mounted on the left side of the phantom at an angle of approximately 45° from vertical. The phantom head and hand is shown in Fig. 1 while Fig. 2 shows the normalized gain patterns as function of the ϕ and θ angle when the handsets are mounted on the phantom behind the phantom hand.

III. Measurements in the Network

In a GSM network, the Abis interface is the interface between the base transceiver station (BTS) and the base-station controller (BSC). Most of the control information transferred between the network and the mobile station (MS) passes the Abis, in particular, the measurement reports (MRs). The MRs contain, among other information, the RxLev measurements, which are measures of the received power levels. The MRs are transferred regularly and are used for handover decisions and power control.

An MR is transferred at least once per second, and usually about twice per second, depending on whether other higher priority frames need to be transmitted on the control channel. The MRs contain measurements for both the UL and DL where GSM handsets are required to perform the power measurements with an accuracy no worse than ± 4 dB. Additionally, the power steps must be, roughly speaking, monotonically increasing with RxLev. The RxLev parameter can take on 64 values and represents the received power in steps of 1 dB [17].

The MRs also contain fields for the BTS TPL as well as an (optional) field for the MS TPL. The BTS TPL field shows in steps of 2 dB from P_n dBm down to $P_n - 30$ dBm the power level used during the last measurement period, where P_n is the cell-specific maximum transmit power and an accuracy of ± 3 dB is required in normal conditions. The MS transmit power is reported in the MRs as absolute values in steps of 2 dB with an accuracy of 2–5 dB, depending on frequency band and level.

Knowing the transmitted power P_t and the received power P_r, the instantaneous link gain can be defined as $G'_\mathrm{l} = P_\mathrm{r} - P_\mathrm{t}$, which is a quantity in decibel. The present paper uses G'_l for comparing the performance of different handsets. Note that a value of 0 dBm is assumed for the unknown P_n. This means that the values of G'_l for the DL direction may be offset by a constant from the correct values, but comparisons are still valid because P_n is the same for all the measurements. The results for the UL direction are in absolute values.

A. In-Network Measurements

The measurement campaign was based on logging the information transferred on the Abis interface of a live GSM network operated by TeleDanmark, a Danish GSM network operator. During the logging, all frames on the Abis were stored for later processing. The logging and post processing of the Abis frames is described in further detail in [11].

The measurements were carried out in a building at Aalborg University where a base station is located approximately 100 m away (see Fig. 3). The base station carries both GSM-900 and GSM-1800 cells and is equipped with vertically polarized and omnidirectional antennas for the two bands, mounted on a mast about 11 m above the ground. Data from both frequency bands are used in the campaign. The measurement building is situated in the outskirts of the city and is a new four-story office building made mainly of reinforced concrete with an outer brick wall.

The measurements took place in corridors of the basement and the second floor, where the basement corridor has walls of concrete and only a few windows and doors. The second floor is an office floor with many windows towards the base station and most inner walls were made of plasterboards. The second floor is about 5 m above the roughly flat ground between the base station and the building. The measurements were made during normal office hours and activity unrelated to the measurement campaign took place. However, the most important area between the base station and the measurement building consists mainly of a parking lot and a bicycle path. Changes here are not expected to be significant to the main propagation paths.

Although, the both bands are available, it should be noted that the network selects to use the GSM-900 band for most of the call duration for calls made on the basement floor, and the GSM-1800 band exclusively on the second floor (see also comments in Section IV-A).

Two types of measurements were made, one series involving 22 live test users and another using the head and hand phantom described in Section II-A. Also, the handsets are identical to the four used during the anechoic room measurements. The two series of measurements were carried out inasmuch the same

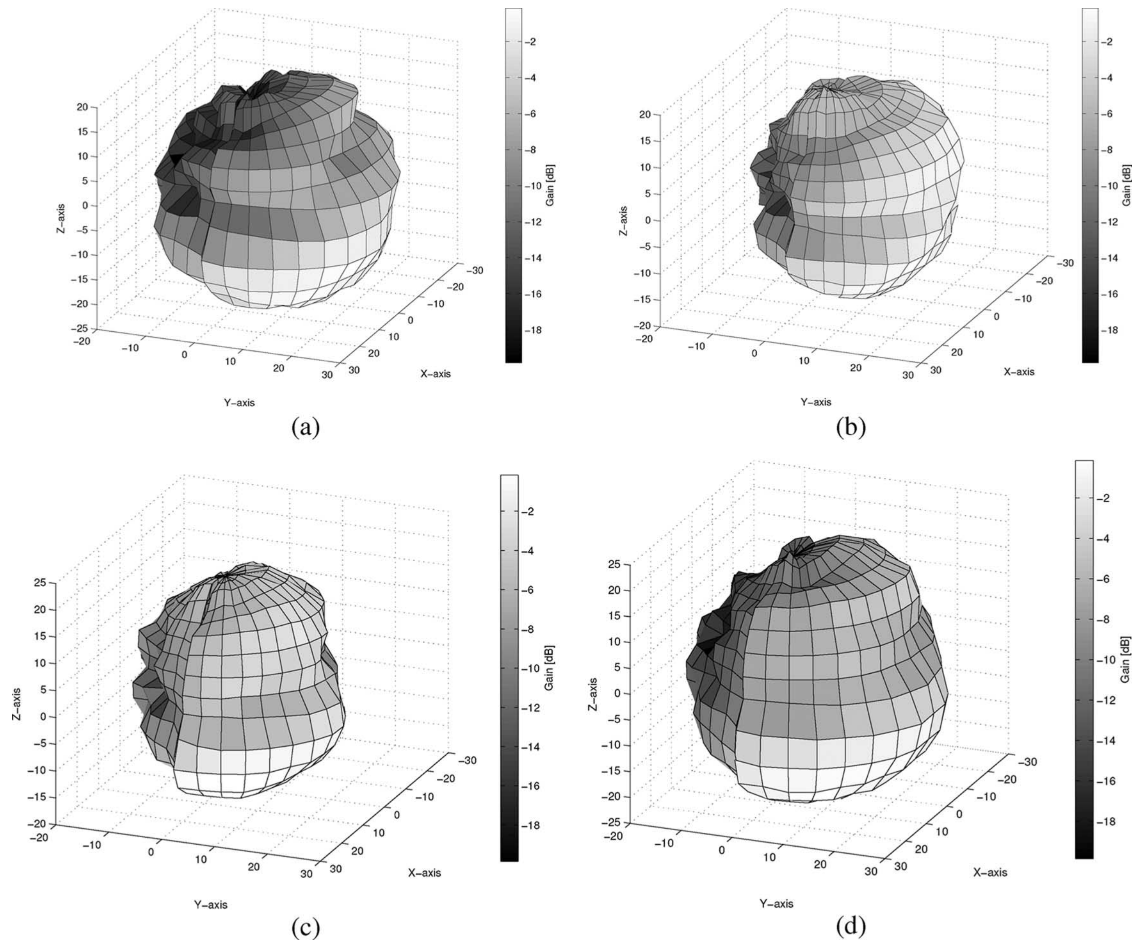


Fig. 2. Measured power pattern of the four handsets in the downlink and next to the phantom. The handsets are mounted on the left side of the phantom. The x- and y-axis of the coordinate system spans the base of the phantom with the x-axis pointing away from the face of the phantom and the y-axis is pointing away from the left ear. The z-axis is directed from the phantom base to the top. (a) Handset A, XPD = 1.8 dB. (b) Handset B, XPD = 1.2 dB. (c) Handset C, XPD = −4.4 dB. (d) Handset D, XPD = −4.5 dB.

Fig. 3. Building in which the measurement took place.

way as possible, and are described below for the case of a test user measurement.

Each measurement starts at the south end of the corridor where the test user stands ready with the handset. A number is entered and the user holds the handset to the ear in the way he or she wants, i.e., the user is not instructed to hold the handset in any particular way. The user starts walking slowly down the middle of the corridor when he or she hears music in the handset. Upon reaching the far end of the corridor, the user turns around and returns in the same way, and the call is ended when the user is back at the initial point. The corridors are about 30 m long. Two measurements are made for each user with each handset and on each floor; one measurement where the user holds the handset in the left hand, and one in the right hand.

To avoid activation of discontinuous transmission (DTX) in the DL direction, the measurements were made by calling an answering machine on which some music was recorded. For the UL, the users carry a portable CD player connected to a small loudspeaker close to the handset microphone.

The phantom series of measurements was conducted with two different tissue-simulating liquids, one specified for 900 MHz and one for 1800 MHz. For each measurement, a call was initiated with the handset, and when connection was obtained, the handset was mounted behind the simulated hand, which was fixed on the left side of the phantom head. At the end of the measurement, the handset was removed from the phantom/hand and the call was ended. The parts of the call used for mounting and dismounting are not included in the later

Fig. 4. Handset mounted on wooden stick for free space measurement in the second floor corridor.

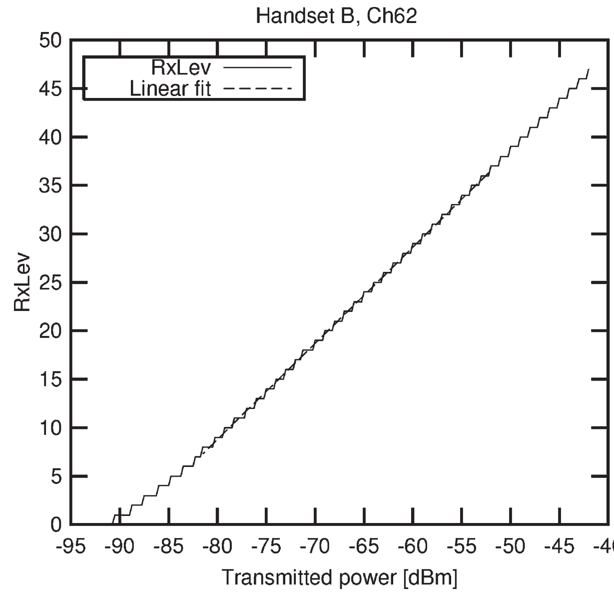


Fig. 5. Reported RxLev value versus transmitted power by the base station.

processing. Two positions of the simulated hand were used; a "low" position where the hand was located approximately 5 cm below the top of the handset, and a "high" position with about 1 cm distance. During the measurements, the phantom was positioned on a wheeled table, which was pushed down the corridor by a person. The table had a height of 78 cm and the distance from the table to the ear of the phantom was 32 cm.

In addition, a number of free space measurements were performed where the handsets were fixed vertically, using tape, to a wooden stick mounted on a trolley (Fig. 4). Two positions were measured for each handset. In the first, called the α position, the handset is mounted with the display facing the direction of motion and at a height of 145 cm above the floor. In the β position, the handset is mounted with the display pointing to the right with respect to the direction of motion and at a height of 105 cm. All free space and phantom measurements were repeated four or five times to allow for averaging and estimation of spread.

B. Measurement Processing

For each received MR, an instantaneous link gain is computed using the RxLev and TPLs, where RxLev is either the "full" or "sub" value depending on whether or not DTX was applied. An estimate of the mean value $\hat{\mu}_{\mathrm{g}}$ of all the instantaneous link-gain values measured during each call is then used as a measure of the link quality

$$\hat{\mu}_{\mathrm{g}} = 10\log_{10}\left\{\frac{1}{N}\sum_{i=0}^{N-1} G_{\mathrm{l}}(i)\right\} \quad (2)$$

where $G_{\mathrm{l}}(i)$ is the ith instantaneous link-gain measurement in linear scale and N is the number of instantaneous link-gain values obtained for the measurement in question. During the measurements, the value of N was 115–310, depending on the person.

The mean link gain may, for the DL, be interpreted as the mean gain of the handset over a hypothetical antenna that collects all the power transmitted by the base station, i.e., all the power in both polarizations and in all directions with a 0 dB gain. For the UL, the reference is the total transmitted power as if the handset was equipped with a lossless antenna with no matching losses. It is noticed that in both cases, the mean link gain includes the polarization matching between the antenna of the handset and the mobile channel.

Also included in the mean link gain is the path loss between the base station and the handset, which may be of minor interest. This is eliminated in the BL measure associated with a call involving a test user or the phantom, which is computed as the difference $\hat{\mu}_{\mathrm{g}}^{\mathrm{free}} - \hat{\mu}_{\mathrm{g}}^{\mathrm{body}}$ between the mean link gain obtained in free space and with the user or phantom, respectively.

C. Errors in Handset Transmit and Receive Power Levels

As noted above, the GSM standard allows the RxLev measurements made by the handsets to deviate from the actually received power level. Since the RxLev measurements are used extensively in this measurement campaign and rather large deviations are allowed, it is worthwhile to establish the actual accuracy of the measurements made by the handsets.

To that end, a GSM tester was used to obtain the RxLev values reported by the handsets for a given power transmitted by the GSM tester, which acts as a base station. During a measurement, the handset was located in an anechoic room where it was oriented to receive maximum power from the base-station antenna.

Fig. 5 shows an example of the RxLev values reported by a handset for different base-station TPLs. Ideally, the curve should be a "staircase" with steps of height and width of exactly 1 dB. In practice, the GSM specifications allow the handsets to deviate considerably from the ideal curve.

With the purpose of investigating the deviation from linearity, a linear regression of the measured RxLev values was computed

TABLE I
MINIMUM AND MAXIMUM VALUES OF THE DIFFERENCE BETWEEN THE MEASURED RXLEV VALUES AND A LINEAR REGRESSION LINE

	GSM-900		GSM-1800	
Handset	Min	Max	Min	Max
A	−0.6	0.7	−0.4	0.6
B	−0.6	0.8	−0.6	0.4
C	−0.5	0.5	−0.5	0.6
D	−0.5	0.5	−0.7	0.5

as function of the input power level. The RxLev values obtained during the measurement campaign obviously varies depending on the environment and all the possible values 0, 1, . . ., 63 are used from time to time. However, due to the power control some values are more likely than others. Table I shows the deviations from the linear regression considering only RxLev values between the 10% and 90% quantiles of the RxLev values actually observed during the measurements. Clearly, the measurements are nearly as linear as possible for the given 1 dB step size.

Because the RxLev curves for all the handsets are essentially linear with the correct slope, any error will be a simple offset, which is constant over the input power levels. The offset is due to the combined losses in the antenna, matching, etc, and errors in the RxLev value measurement. It is possible to determine this offset; in this paper, however, this calibration was not carried out since mostly relative BL values are used. In Section V, the measurements made in the network are compared to measurements carried out in the anechoic room, but the latter measurements are also based on RxLev values and hence any offsets will also be part of these measurements. It may also be noted that although the measurements based on the RxLev values may be offset from an antenna-measurement point of view, these are indeed the values used in the network during normal operation.

The TPLs used by the handset during a measurement are reported to the network and these values are used to compute the instantaneous link gain. Therefore, a difference of the actual TPL from the nominal TPL leads to an error in the UL link-gain result. In this way, a handset with a power amplifier transmitting at a lower level than reported may be indistinguishable from a handset where the power amplifier outputs the correct level but has an antenna with low efficiency. Again, from a network point of view there is no difference.

Using the GSM test base station, the error in the transmit power can be measured for the handsets with an RF connector. Unfortunately, handset C does not have an external RF connector but for the remaining three handsets a maximum deviation from linearity of 0.2–1.0 dB was found in addition to an offset of 0–0.8 dB, both depending on the handset and frequency band. As for the RxLev values, offset errors will be included in both the network measurements and the anechoic room measurements.

IV. IN-NETWORK MEASUREMENT RESULTS

A. Free Space

Table II shows the results for the UL case. The measurement for each combination of handset, position, and floor was repeated five times and the table shows mean link gain (Gain) and standard deviation (STD) computed from these repeated measurements. In each case also, the maximum difference among the five measurements is given (max–min). In 4 of the total 32 cases (both UL and DL), only four measurements were successfully obtained due to, e.g., handover during the measurement. The number of measurements is also shown (No).

Depending on which handset, position, etc, the max–min value is 0.2–1.3 dB. Although values up to 1.3 dB were found, most (30 out of 32 UL/DL results) show differences less than or equal to 1.0 dB. These values indicate the accuracy of the measurement procedure itself, since the free space measurements involve very little “handling” of the handsets that may introduce additional changes in the observed channel.

It is interesting to compare the mean link gains obtained on the basement floor with the corresponding values on the second floor, where the latter seems to have about 16 dB more link gain than the former. There are two reasons for this difference. The first is the difference in environment, where the path loss to the basement can be expected to be much larger than when the handset is on the second floor, where windows allow the signal to penetrate the building more easily. Second, on the second floor, the 1800 MHz band was always used, whereas on the basement floor the 900 MHz band was used around 95% of each call.

From the table, it is noted that the differences in using the α and β positions are low—less than 0.8 dB for the UL and 1.1 dB for the DL and any combination of level and handset.

Table III shows a comparison of the free space link gains for the various handsets, where the mean of the two positions is used and the values are normalized to the highest link gain for each floor and UL/DL combination. In all cases, handset C has the highest link gain but the performance of the remaining handsets depend on the floor and whether UL or DL is compared. However, all values are within 2.5 dB.

B. BL for Test Users

The mean of the measured BLs are shown in Fig. 6 and analyzed in the following.

1) BL Difference for UL/DL: Comparing the results for UL and DL obtained with the same handset, side, and environment, it is found that for the basement floor the mean values are within 1 dB, where the DL value is largest for five of the eight pairs of values. Also, for the second floor the differences are within about 1 dB, except handset C that has a difference of 1.6 and 2.2 dB for the left and right side usage, respectively. Thus, for handset C the UL mean BL is clearly larger than the DL mean BL on the second floor where the 1800 MHz band is used. This might be due to a matching problem of the power amplifier in the handset. Also, the different environments on the two floors may have some influence.

2) Differences in Mean BL Due to Head Side: For the basement floor, handset A has about 3.1 dB more BL when used in the left hand than in the right hand. Conversely, the right-hand BL is about 4.7 dB larger than the left-hand BL for handset D. Both of these handsets have external antennas but

TABLE II
FREE SPACE RESULTS FOR THE UL. THE MEAN LINK GAIN, STD, MAXIMUM DIFFERENCE, ALL IN DECIBELS, AND THE NUMBER OF SUCCESSFUL MEASUREMENTS

		Basement				2nd Floor			
Handset	Pos.	Gain	Std	Max–Min	No	Gain	Std	Max–Min	No
A	α	−111.3	0.1	0.2	4	−95.5	0.4	0.8	5
	β	−112.1	0.3	0.7	5	−95.9	0.2	0.6	5
B	α	−110.0	0.4	0.9	5	−94.3	0.2	0.4	4
	β	−110.1	0.3	0.8	5	−94.4	0.3	0.8	5
C	α	−109.6	0.3	0.7	5	−93.0	0.2	0.6	5
	β	−110.3	0.4	1.0	5	−93.4	0.2	0.5	5
D	α	−109.9	0.4	0.9	5	−94.2	0.2	0.6	5
	β	−110.7	0.5	1.3	5	−94.0	0.3	0.6	5

TABLE III
NORMALIZED MEAN LINK GAIN FOR FREE SPACE

	Up-link		Down-link	
Handset	Bse	2nd	Bse	2nd
A	−1.8	−2.5	−0.6	−0.4
B	−0.1	−1.2	−0.2	−2.0
C	0.0	0.0	0.0	0.0
D	−0.3	−0.9	−0.6	−0.8

placed in opposite sides of the handset, left side for handset D and right side for handset A. An obvious explanation for the differences in BL is that when a handset with a right side mounted antenna is used in the left hand, the antenna is closer to the person's ear/head than when used in the right hand, and similarly handsets with left side mounted antennas have the lowest BL when used in left hand. However, this is not the case on the second floor where handset A has about 0.2 dB difference for the two sides and handset D has about 0.7 dB higher BL in right hand than in left hand. The most likely explanation for this is that the antennas behave differently for the 900 and 1800 MHz bands used at the basement and second floor, respectively.

Handsets B and C with internal antennas also show some asymmetry for the basement floor, where the right-hand BL is about 1.6 dB larger and about 1.4 dB smaller, respectively, than the left-hand BL. For the second floor, the tendency is still the same but the differences are only about 0.5 dB. The above comments are for the UL direction, but the pattern essentially repeats for the DL direction, although the left/right differences are somewhat different.

3) Mean BL Variation Over Handsets: Generally, handsets A and D with external antennas have the lowest BL among the four, if used in the best side, with handset A slightly worse than handset D. Table IV shows the mean BL for all combinations of handset, level, and direction, where the handset is always used in the best side. It is noticed that there is a clear ranking; handsets A or D always has the lowest BL, then follows handsets B, and C. Moreover, the handsets with internal antennas have a 2 dB larger BL compared to handsets with external antennas, which have a mean BL of approximately 6.25 dB. It is noted from Fig. 6 that the handsets with external antennas may have a much higher BL if used in the "wrong" side, in which case, the BL on the basement floor is comparable or even higher to what is found for the handsets with internal antennas.

C. STD Among Test Users

The STD of the link gain obtained with the different users may be used as a measure of the variation in the power caused by the users. Furthermore, the relative STD (RSTD) is defined as the ratio of the STD and the corresponding mean BL. The RSTD is in the range 16%–55% for the left side and 14%–43% for the right side with the majority of values above 20% in both cases. The STD is to some degree independent of the building level and therefore the RSTD is always lower on the basement floor than on the second floor for all handsets when used in left hand. The same is true for right-hand usage, except handset B, which has the minimum values of about 14% and 18% for the UL and DL directions, respectively.

Handset C has an STD of about 3.5–4 dB on the second floor for the UL compared to about 2–2.6 dB for the remaining handsets. Also, in the DL direction, handset C has the largest STD, except for the right side where handset D has an STD of about the same. All the STD values are given in Fig. 7.

For the basement floor, the ranking is less clear. On this floor, handset D has the largest STD of about 4 dB for right side usage in the DL direction; handset C used in the left hand has an STD of about 3.4 dB, which is approximately 1 dB more than the other two handsets (for both sides).

Although the picture is somewhat unclear, the following three classes of STD values can be identified:

Small: 1–1.5 dB. These values of STD are only obtained by handsets A and B for right-hand usage.
Average: 1.5–2.5 dB. All handsets have values in this class.
Large: 2.5–4.5 dB. These are only obtained by handsets C and D.

From this, it is noted that none of the small handsets are in the small STD class and furthermore that none of the large handsets are in the large STD class. Therefore, it seems that large handsets often lead to a smaller variation in the BL as compared to small handsets.

D. BL for Head Phantom

On the basement floor essentially only the 900 MHz band is used and on the second floor the 1800 MHz band is used exclusively. Although measurements with both 900 and 1800 MHz liquids were conducted on both floors, the following considers only the 900 MHz liquid on the basement floor and only the 1800 MHz liquid is considered on the second floor.

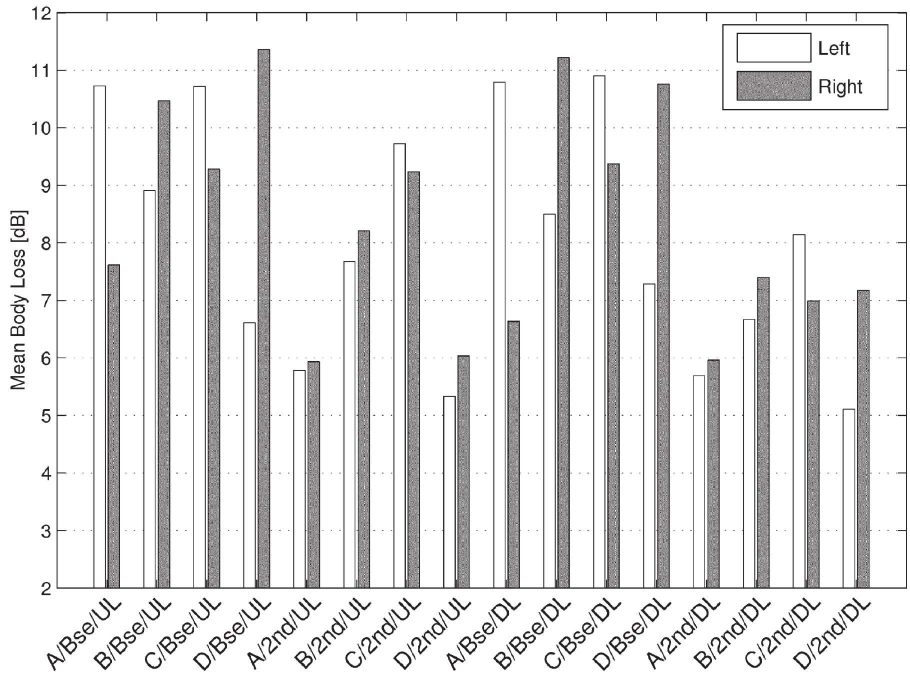


Fig. 6. Mean BL for test persons using handsets A–D on the basement and second floor. On the second floor, the calls are made in the 1800 MHz band while the 900 MHz band is used for more than 95% of each call on the basement floor. Results are shown for both the UL (mobile transmit) and DL.

TABLE IV
BL IN DECIBELS WHEN THE HANDSETS ARE USED IN THE BEST SIDE

	Up-link		Down-link		
Handset	Bse	2nd	Bse	2nd	Mean
A	7.6	5.8	6.6	5.7	6.4
B	8.9	7.7	8.5	6.7	7.9
C	9.3	9.2	9.4	7.0	8.7
D	6.6	5.3	7.3	5.1	6.1

An investigation of the liquid-type influence on the performance is presented in [18].

The mean BLs obtained with the phantom are shown in Fig. 8 where also the corresponding mean BLs obtained with test users are shown. Since all the measurements with the phantom were made on the left side of the head, only results for left-hand measurements are shown for the test users. Note that no data are available for handset D on the basement floor and the high position of the phantom hand.

Comparing the mean BLs obtained for the UL and DL directions, all differences are less than about ± 1 dB, except for handsets B–D on the second floor and the high hand position, which have 1–1.5 dB higher BL in the UL than in the DL. As noted in Section IV-B1, a similar difference was also found for the real user case and handset C.

When comparing the BLs obtained for the high and low positions of the hand, the high hand position in most cases leads to a BL larger than that obtained with the corresponding low hand position. This is expected and has been found previously with live test users [19]. However, for handset B on the basement floor, the opposite was actually observed; in this case, the low hand position had 2.5–3 dB higher BL than the high hand position. This is surprising since handset B has an internal antenna. For handset A on the basement floor, the BL is about the same for the two hand positions. The hand position might be less important for this handset because of the external antenna.

Comparing the mean BL over the handsets for the two floors it is found that the basement floor has about 6.4 dB higher BL than the second floor for the low hand position and about 6.2 dB for the high hand position. The similar figure obtained with the real users is about 2.5 dB, and therefore the measurements with the phantom seem to exaggerate the difference in BL for the two floors where different frequency bands are used. It can be noted that the difference in BL on the two frequency bands was investigated in [20] using measured radiation patterns of handsets mounted on phantoms. In this paper, the BL was found to be about 3 dB higher for the 900 MHz band than for the 1800 MHz band.

The measurements involving test users show that for the handsets with external antenna the BL is highly dependent on the side in which the handset is used, probably due to the asymmetric position of the antennas on the handsets. For left-hand usage, handset D has 3–4 dB lower mean BL than handset A on the basement floor. All the measurements with the phantom were made on the left side of the head, where for the basement floor and the low position of the hand, the difference in BL of handsets A and D is about 1.9 dB for the UL and about 0.8 dB for the DL direction. Thus, the performance difference due to the handset asymmetry is not revealed by the phantom measurements. One likely reason for this is that due to the different designs and sizes, the handsets are held differently by the test persons, and this is difficult to reproduce with the phantom hand.

Handsets A and D always have the two lowest BL values, and handsets B and C with internal antennas always have the two highest BLs, with the exact ordering depending on level, link direction, and position of the hand. This grouping of handsets with external antennas having lower BL than those with internal

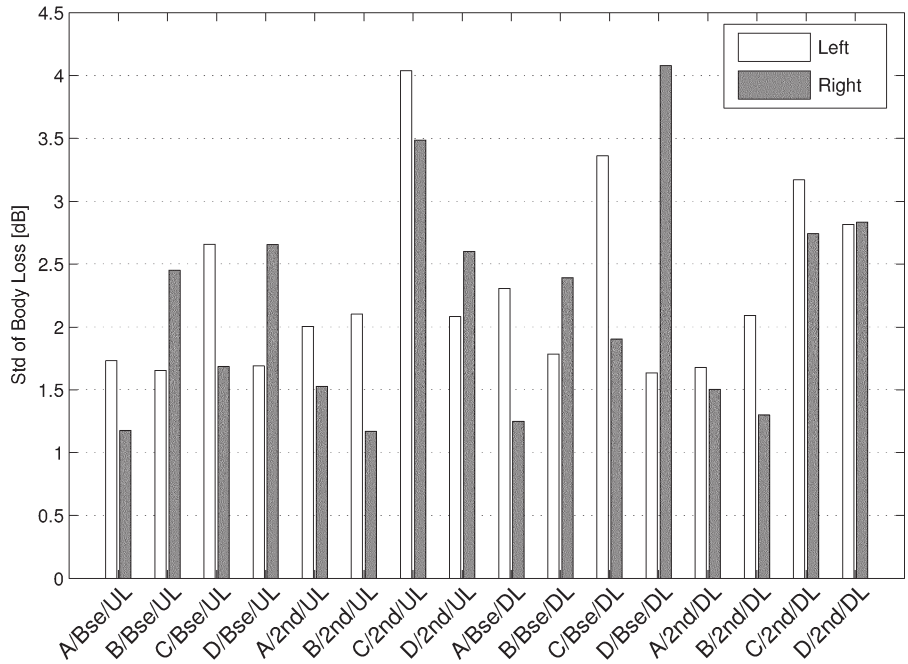


Fig. 7. STD of the BLs for test persons using handsets A–D on the basement and second floor. On the second floor, the calls are made in the 1800 MHz band, while the 900 MHz band is used for more than 95% of each call on the basement floor. Results are shown for both the UL (mobile transmit) and DL.

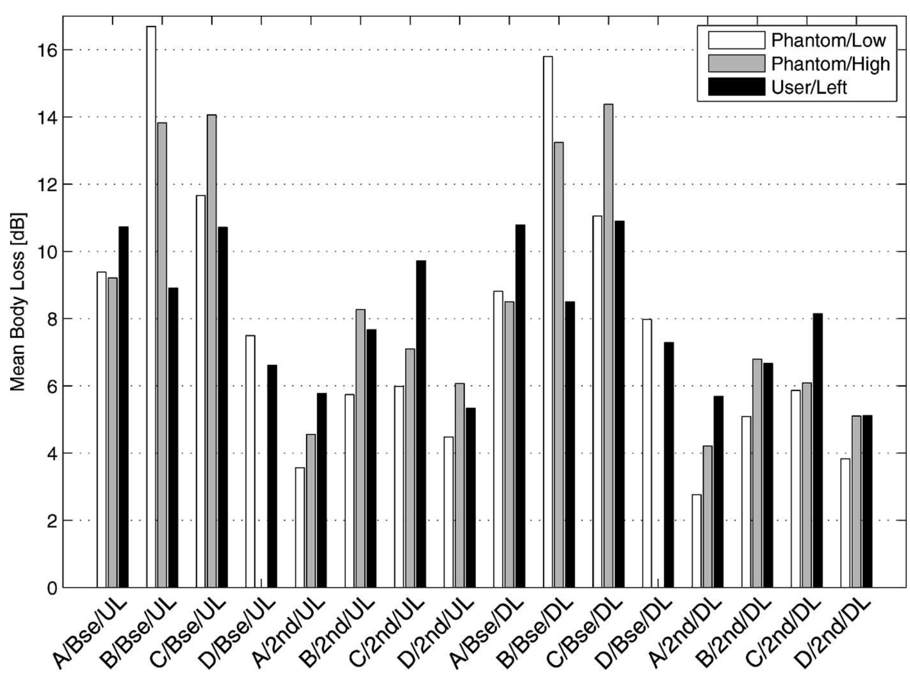


Fig. 8. Comparison of the mean BL obtained with test users and the phantom for handsets A–D on the basement and second floor. On the second floor, the calls are made in the 1800 MHz band, while the 900 MHz band is used for more than 95% of each call on the basement floor. Results are shown for both the UL (mobile transmit) and DL.

antennas was also found for the real user case, on the condition that the handsets with external antennas are used in the "best" side. Therefore, though the phantom measurements cannot detect the difference in BL due to the side used, as mentioned above, there seems to be some differentiation among the types of handsets.

Fig. 8 allows a comparison of the absolute values of the BL obtained with the phantom and the corresponding mean BL values obtained with the real users. Significant differences are evident, up to about 7.5 dB. The curves suggest an offset depending on the floor, as investigated in Table V. The table shows the BL difference for the high and low hand positions, averaged over the different handsets and the two link directions. As expected the figures in the table suggest that the BL obtained with the phantom is too large in the mean on the basement floor where the 900 MHz is used mainly, whereas on the second floor where the 1800 MHz band is used, the obtained BL tends to be too low.

TABLE V
OFFSET OF THE BL MEASURED WITH PHANTOM FROM REAL USER CASE. MEAN OVER HANDSETS AND LINK DIRECTIONS

Level	Low Pos.	High Pos.
Bse	1.8	2.1
2nd	−2.1	−0.7

E. STD for Phantom Measurements

The STD of the repeated measurements is below 0.8 dB for all the measurements with a few exceptions, namely four cases for handset B and the high position of the hand (1.5–2 dB) and one case for handset D for the low hand position (3.3 dB), the latter case obtained when the 900 MHz liquid was used on the second floor.

The high STD values obtained with handset B are for the second floor where the 1800 MHz band is used. It is unclear why the measurements for especially handset B seem to have a larger variation than the other handsets. Generally the STD is quite low with only 22% (14 of a total 60) exceeding 0.6 dB. This is a surprisingly small variation, considering that for each measurement the handset had to be repositioned behind the simulated hand.

The STD is below 15% of the mean BL with a few exceptions, most of which are coinciding with the large STD values mentioned above.

F. Hand Position and BL

In [19], the user's position of the hand on the handset was found to be correlated with the radiation efficiency of the handset. The radiation efficiency was approximately constant independent of the user's hand position, for situations where the hand covers up to 10 cm measured from the bottom of the 13 cm high handset. When the user's hand entered the top 3 cm of the handset, the efficiency decreased with higher hand positions.

For each of the current measurements where the handset was held by a user, a picture was taken, so that the exact hand position was recorded for later use. From each picture, the position of the user's hand was determined visually to belong to one of four categories, defined as follows. If any part of the user's hand and fingers is

1) more than 30 mm from the top of the handset body;
2) between 30 and 15 mm from the handset top;
3) less than 15 mm from the handset top;
4) touching the antenna (only for handsets with external antennas);

then the hand position is labeled accordingly. Using these labels the correlation between BL and hand position can be investigated, as in Fig. 9, where both the BL and the hand position are shown. The measurements have been sorted for increasing BL.

In Fig. 9(b), for handset C it is noticed that for the majority of the measurements with the largest BL the user holds the handset so that the hand enters the top 15 mm (hand position 3). Furthermore, the lower values of BL are generally obtained by users holding the handset in position 1 and 2, thus indicating there is some connection between hand position and BL.

A convenient measure of how the BL depends on the hand position is the following. After sorting for increasing BL the set of measurements is divided into a lower half and an upper half. The skewness in the distribution of the hand positions is then measured by $s_\mathrm{r} = \mu_\mathrm{up}/\mu_\mathrm{low}$, where μ_low and μ_up is the mean of the hand positions in the lower and upper half, respectively. Values of s_r roughly equal to one then indicate that the hand positions are equally distributed, although the BL values are sorted. The hand positions tend to be higher in one half than in the other if s_r is higher or lower than one. Table VI shows the values of s_r for all the measurements. The values of s_r are also given in Fig. 9. Note that on the second floor some pictures are missing and hence the computation of s_r is based on 8–10 measurements on this floor; on the basement floor, 20–22 measurements were used.

First, it is worth noting that there are generally only small differences in the s_r values obtained for the UL direction and the corresponding values for the DL direction, with differences of 0–0.1 in most cases. However, there are exceptions for the basement floor where the s_r values differ up to 0.4 between the UL and DL directions.

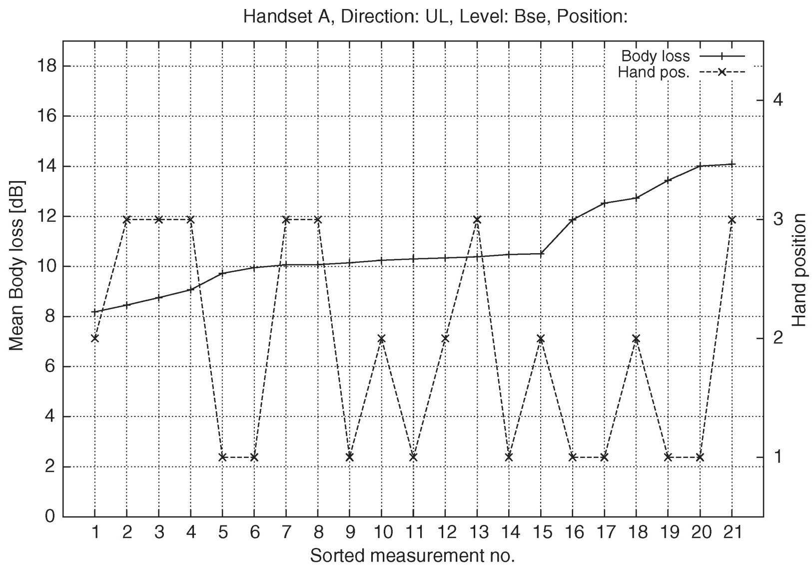
The handsets are generally insensitive to which side they are used in, except handsets A and C on the basement floor, the latter only for the UL. These handsets seem, to some degree, to behave oppositely for the two sides (see also below).

As mentioned in Section IV-B2, the average BL for handset D is largest when used in right hand because the antenna is located in the left side of the handset, which means that the antenna on average will be closer to the user's head/ear than if it is used in the left hand. The opposite was found for handset A, which has the antenna mounted in the right-hand side. Therefore, the distance from the antenna to the user's head/ear is important. In normal use, this distance depends on the distance between the low end of the handset and the user's head or cheek. Because of the small size of handset D, a low hand position might be combined with a larger distance between the head and the low handset end than if the hand is held high on the handset. This might explain the s_r values of 0.7–0.9 in Table VI for handset D, which indicate that on average a high hand position leads to a lower BL than a low hand position.

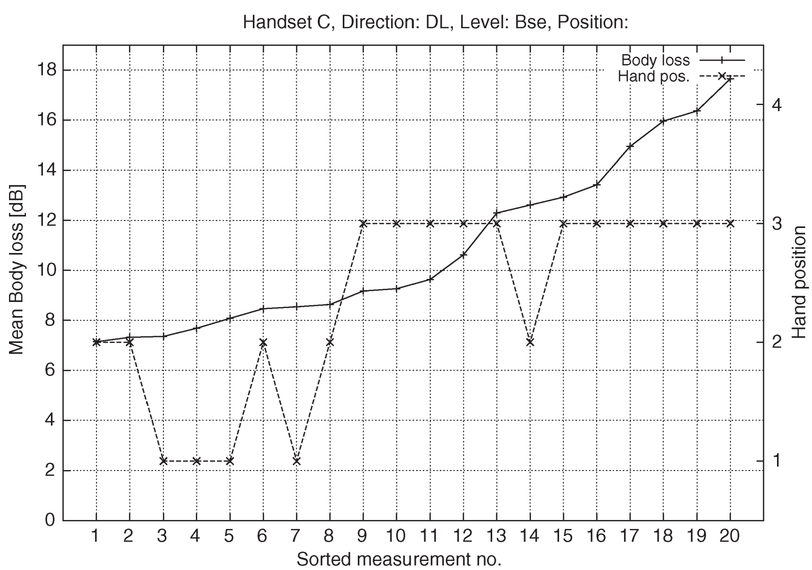
The drawback of a high hand position is that the user probably will cover more of the handset and therefore may result in a higher BL, as found for the phantom head and hand in Section IV-D. Hence, for handsets with external antennas it may be a question of which effect is dominating. This might explain why the s_r value for left-hand usage of handset A on the basement floor is less than one, while it is greater than one for right-hand usage.

For handsets B and C with internal antennas, the s_r values are all greater than one, except for handset B, UL on the basement floor, thus supporting the notion that the BL increases when the user's hand cover larger parts of the handset. Furthermore, most s_r values are larger for handset C than for handset B, indicating that the smaller handset is more sensitive to the hand position.

The possibility that the values of s_r depend on the amount of variation in the BL was checked by correlating the STD of the BL values with the corresponding values of s_r. Essentially no correlation was found (a correlation of 0.04).



(a)



(b)

Fig. 9. Sorted BL and associated hand position for handsets A (top) and C (bottom) in the downlink direction, the basement floor, and left-hand usage. Handset A: $s_\mathrm{r} = 0.7$. Handset C: $s_\mathrm{r} = 1.6$.

TABLE VI
RATIO OF MEAN HIGH AND LOW POSITIONS s_r

		Up-link		Down-link	
Handset	Pos.	Bse	2nd	Bse	2nd
A	L	0.7	1.2	0.7	1.2
	R	1.2	1.4	1.2	1.4
B	L	0.9	1.4	1.3	1.4
	R	1.1	1.3	1.1	1.3
C	L	1.4	1.5	1.6	1.5
	R	1.0	1.5	1.3	1.5
D	L	0.9	0.8	0.9	0.7
	R	0.8	0.9	0.8	0.7

V. COMPARISON OF IN-NETWORK AND ANECHOIC ROOM RESULTS

The MEG is computed using a discrete version of (1). Since both the radiation pattern and the environment models (at least the AAU model) are directional the MEG generally depends on the orientation of the handset with respect to the environment. Unfortunately, the orientations of the test users and the phantom during the measurements were not recorded and therefore it is not possible to evaluate directional dependence of the MEG directly—for example, compare the mean link gain for the forward and return parts of the measurement path. However, the nonuniform power distribution is included in the in-network measurements and hence must also be represented in the MEG values computed using the radiation patterns.

The second floor has windows towards the base station and it is assumed that most of the received signals arrive from that angle, so that two different orientations of the handset need to be considered, corresponding to the forward and return paths when the handsets are measured in the corridor. The MEG considered in the following is the average of the two MEG values obtained for the two orientations of the handsets.

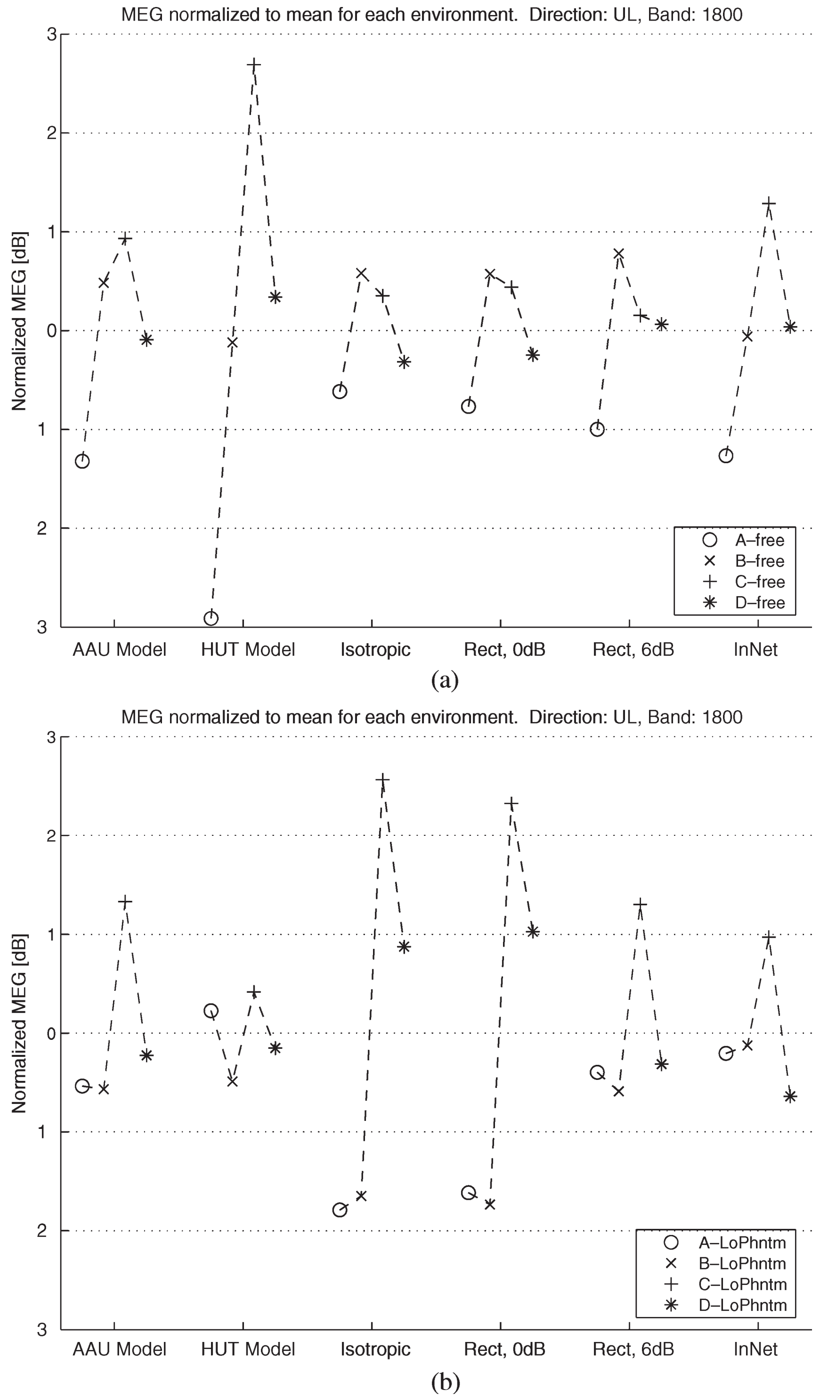


Fig. 10. Comparison of MEG obtained via spherical radiation patterns and MEG measured in the GSM network. (a) Free space UL. (b) Phantom UL.

Fig. 10 displays the MEG results for the different environments and also the results based on the Abis measurements are included. Since the absolute level is unknown, the values have been normalized individually for each environment using the average of the MEG values obtained for the different handsets.

For free space, the results for the isotropic and the two rectangular models are very similar. The area covered by the rectangular models is more than 71% of the sphere and therefore the power included is close to that of the isotropic model. In free space, the four handsets have an XPD in the range 4–8 dB, and therefore, the rectangular model with an XPD of 6 dB only roughly introduces a scaling of all MEG results, which is removed by the normalization.

The results for the AAU, rectangular, and isotropic models all fall within about ± 1 dB difference between the handsets obtained for the in-network measurements, at least for the DL. The same is true for the UL, except for the Rect 6 dB model and handset C, where a deviation of 1.1 dB is obtained. For both link directions, the HUT model exaggerates the differences between the handsets.

For the phantom measurements, it is interesting to note the difference in the results obtained with the rectangular, 0 dB

TABLE VII
MEAN OF DIFFERENCES BETWEEN IN-NETWORK AND ANECHOIC ROOM RESULTS

	Free		Phantom	
Environment	DL	UL	DL	UL
AAU	0.6	0.3	0.4	0.4
HUT	1.7	0.9	0.3	0.5
Isotropic	0.3	0.6	1.4	1.6
Rect, 0 dB	0.3	0.6	1.4	1.5
Rect, 6 dB	0.4	0.6	0.4	0.3

XPD model from the results obtained the rectangular, 6 dB XPD model. The only difference between the two models is the weighting of the power received in the two polarizations. Handsets C and D has an XPD of −4.5 dB down to −5.5 dB, and thus most power is received or transmitted in the ϕ polarization. Therefore, these handsets perform much better with the rectangular, 0 dB model than the 6 dB model. Judging from the fact that the rectangular, 6 dB model yields results that are much closer to the network results than does the rectangular, 0 dB and isotropic models, it seems likely that the XPD of the latter two models is unrealistic. The results obtained with the AAU model and the rectangular model with an XPD of 6 dB are both rather close to those obtained from network measurements. This suggests that, in this case, the shape of the environment model is not critical. It may be recalled that the AAU model has an XPD of 5.5 dB.

Table VII shows the mean absolute difference between the in-network results and the results obtained via the radiation patterns, where the mean is over the different handsets.

VI. CONCLUSION

The MEG is the appropriate measure of the ability of a mobile handset to receive and transmit power where both the properties of the handset antenna and the mobile channel is taken into account. For realistic MEG values, a number of handset users must be involved so that the average performance and the variation can be computed. One of the main goals of the current work was to carry out a comparison of the performance measures obtained with some proposed simpler evaluation methods and the measures obtained with a reference method. The reference method evaluates the handset in a live GSM network during normal calls and hence in realistic situations. These measurements involved 22 test users in two different indoor environments.

A first step to simplify measurements is to use a phantom simulating the influence of the user's hand and upper parts of the body. In order to investigate whether a phantom produces essentially the same results as the average test user, a series of measurements were made with the phantom in the same way as with the test users. Finally, the performance of the handsets was also evaluated using spherical radiation patterns measured in an anechoic room. The radiation patterns allow computation of the TRP and the TIS for the UL and downlink, respectively, as well as other measures, depending on the applied channel model.

Four different commercially available handsets of different size and type were used for the investigation. The performance evaluation in the network showed that for the free space case all mean link gains were within 2.5 dB, where the small handset with internal antenna had the highest mean link gain in all cases. The BL is the decrease of the link gain when a user is present with the free space case as reference. The mean BL was found to be in the range 5–11 dB depending on handset, side, and building level (including frequency band).

For the 900 MHz band, the handsets with external antennas show a difference in BL of 3–4.5 dB, most likely due to the asymmetry of the handsets, since the handset with a left mounted antenna has lowest BL when used in the left side, and vice versa for the handset with a right-hand-mounted antenna. The handsets with internal antennas have smaller differences with respect to side of usage. The differences are not as clearly present for the 1800 MHz band. Assuming that the handsets are used in the best side, the BL for handsets with external antennas is on average about 2 dB lower than for handsets with internal antennas. The BL seems to be larger for small handsets than for large handsets, on the average about 0.8 and 0.3 dB for the handsets with internal and external antennas, respectively. Similarly, there is a tendency that small handsets are more sensitive towards the influence of the user, as seen by the STD of the BL measured with the different test users. The STD is 14%–55% of the BL, indicating that the BL in some cases varies significantly among the users.

Investigations of the position of the user's hand on the handset seem to verify previously published results that the BL is highest when the hand is placed closest to the top of the handset. However, the results also indicate that for handsets with external antennas a high hand position in some cases may be preferable for a small handset.

Significant differences were noted comparing the BL observed with the phantom with the mean BL observed for the real user, up to 7.5 dB in some cases. Generally, the BL obtained with the phantom seems to be too large on the basement floor where the 900 MHz band is used, and too small on the second floor were the 1800 MHz band is used. The difference in BL because of the handset asymmetry observed in the real user case, was not revealed by the phantom head, probably due to inaccurate modeling of the different ways of holding the handset. In conclusion, the tested phantom and hand model seems unsuitable as a replacement of the real users in BL measurements.

In comparing the results obtained in the network with results based on spherical radiation patterns, the best results seem to be obtained with either the rectangular model with an XPD of 6 dB or the AAU model, which both results in average absolute deviations of up to 0.6 dB. The results obtained with the isotropic model (i.e., TRP and TIS values) do not match the results obtained with the network well, with mean deviations up to 1.6 dB. The deviation figures should be compared to the MEG difference for the handsets of 2–2.5 dB.

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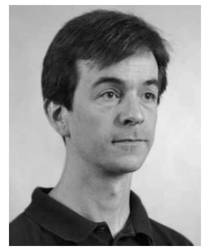

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